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Characteristics and variability of the vertical thermohaline structure in the Gulf of Finland in summer

Taavi Liblik* and Urmas Lips

Marine Systems Institute at the Tallinn University of Technology, Akadeemia Road 21, EE-12618 Tallinn, Estonia (corresponding author's e-mail: taavi.liblik@gmail.com)

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Vertical profiles of temperature and salinity collected in the summers of 1987–2008 were analyzed in order to describe the mean characteristics and variability of the vertical termohaline structure in the Gulf of Finland. Quantitative estimates of the mean characteristics of the upper mixed layer, seasonal thermocline, cold intermediate layer, halocline and deep layer as well as their along-gulf changes were obtained. Both the long-term (inter-annual) and short term variations in the thermohaline structure were related to the changes in the atmospheric forcing. Two distinct periods with statistically different mean temperature and salinity in the deep layer were detected among the analyzed 22 years. The overall vertical salinity (and density) gradient was much stronger and the halocline was sharper in the recent years than in the years 1987–1990. However, the summer mean vertical salinity and density gradients in the seasonal thermocline did not reveal large inter-annual variations. We suggest that a possible shift towards fresher waters in the Baltic Sea due to the climate change would result in the two-layer structure of water column in the deeper areas of the Gulf of Finland in summer. At the same time, a possible increase of sea surface temperature could lead to a strengthening of the vertical density stratification in the seasonal thermocline.

Introduction

The Gulf of Finland is a 400-km-long and 48–135-km-wide, elongated sub-basin of the Baltic Sea. It covers approximately 29 600 km^2 and its volume is 1100 km^3 (Alenius *et al*. 1998). It has no sill at the entrance area separating the Gulf from the open Baltic Sea and its maximum cross-section depth decreases from > 100 m at the entrance to < 30 m in the eastern part. The Gulf receives 3556 m^3 s^{-1} (70-year average) of river discharge (annually 10% of the volume of the Gulf) that is mainly concentrated in the easternmost part of the Gulf (Bergström and Carlsson 1994). Therefore, the salinity distribution in the surface layer is characterized by an increase from 1–3 in the east to 6 (on the Practical Salinity Scale) in the west. Also a slight decrease across the Gulf from south to north exists.

The characteristics and seasonal development of vertical stratification in the Gulf of Finland was quite thoroughly described by Alenius *et al*. (1998) using data collected until 1996. The water column in the deeper areas of the Gulf reveals a three-layer vertical structure in summer — the upper mixed layer, the cold intermediate layer and the near-bottom layer, which is saltier and slightly warmer, can be distinguished. These layers are separated by the two pycnoclines — the seasonal thermocline usually situated at the depths of 10–20 m and the permanent halocline at the depths of 60–70 m.

According to the HELCOM monitoring data, a decrease in salinity of the deep layers of the Gulf of Finland, observed from the late 1970s, was replaced by a salinity increase in the 1990s (HELCOM 2002). During the same monitoring period an average surface layer temperature increase was observed (e.g. Suikkanen *et al.* 2007). It has been reported that the summer sea surface temperatures of the North and Baltic Seas have increased since 1985 at a rate equalling 3 times the global rate, and 2–5 times faster than in other seasons (MacKenzie and Schiedek 2007). An analysis of the remote sensing data from 1990–2004 has revealed strong positive trends in the sea surface temperature in the Baltic Sea in July and August as well (Siegel *et al.* 2006). These long-term salinity and temperature trends are superimposed by relatively large inter-annual variations in the Gulf of Finland, which are well visible, for instance, as variations in the ice conditions (Jaagus 2006) and deep layer salinity (Alenius *et al.* 1998). Both the long-term trends and inter-annual variations in hydrographic conditions affect the Gulf of Finland's ecosystem through, for instance, changes in inorganic phosphorus pool due to the benthic release of phosphorus (Pitkänen *et al.* 2001), changes in phytoplankton community composition (Suikkanen *et al.* 2007) or high inter-annual variability of the late-summer cyanobacteria blooms (e.g. Lips and Lips 2008).

Due to the variable wind forcing and the width of the Gulf, well greater than the internal Rossby radius (Alenius *et al.* 2003), the meso-scale processes and related changes in the vertical thermohaline structure are dominant dynamical features of the Gulf of Finland. Frequent coastal upwelling events affect remarkably the spatial distribution of the sea surface temperature that is visible on remote sensing images (*see* e.g. an analysis by Uiboupin and Laanemets 2009), and the vertical thermohaline structure (e.g. Lips *et al.* 2009). It has also been shown that, depending on prevailing wind conditions, an ordinary estuarine circulation may be altered or even reversed if the southwesterly wind component exceeds the mean value by at least 4–5.5 m s^{-1} (Elken *et al.* 2003) resulting in a drastic weakening of the vertical stratification in the Gulf of Finland. Thus, the wind induced circulation and mixing modify the thermohaline structure in both a short-term (synoptic) and a long-term (from a month to a season) scale. We assume that similarly to the inter-annual variations in the atmospheric forcing defined as the North Atlantic Oscillation (NAO) index (Jones *et al.* 1997) or the Baltic Sea Index (hereafter BSI) (Lehmann *et al.* 2002) it could be possible also to indicate related inter-annual variations in the vertical stratification of the Gulf of Finland water column.

The main aim of the present study was to describe the vertical structure of temperature and salinity fields and its inter-annual variations in the Gulf of Finland in summer (June–August) using the data collected in 1987–2008. The latest descriptions of the hydrographic conditions in the Gulf of Finland have mainly been based on modeling studies [*see* e.g. a paper by Andrejev *et al.* (2004) and a review by Soomere *et al.* (2009)]. In comparison with the study by Alenius *et al.* (1998), the present analysis includes also the years after the mid-1990s when according to the HELCOM monitoring data (HELCOM 2002) an increase of salinity in the deep layers of the Gulf of Finland has occurred. Based on the results we suggest possible changes in the vertical thermohaline structure of the Gulf of Finland taking into account the projections of future anthropogenic climate change (BACC 2008).

Data and methods

The data analyzed in the present paper were collected in 1987–2008 during various research projects and monitoring programs run by the Marine Systems Institute at Tallinn University of Technology and its predecessors. Vertical profiles of temperature and salinity were obtained using Neil Brown Mark III and Sea-Bird SBE-19 CTD (conductivity, temperature, depth) profilers. The salinity values were calculated using algorithms from Fofonoff and Millard (1983) and are presented without units on the Practical Salinity Scale 1978.

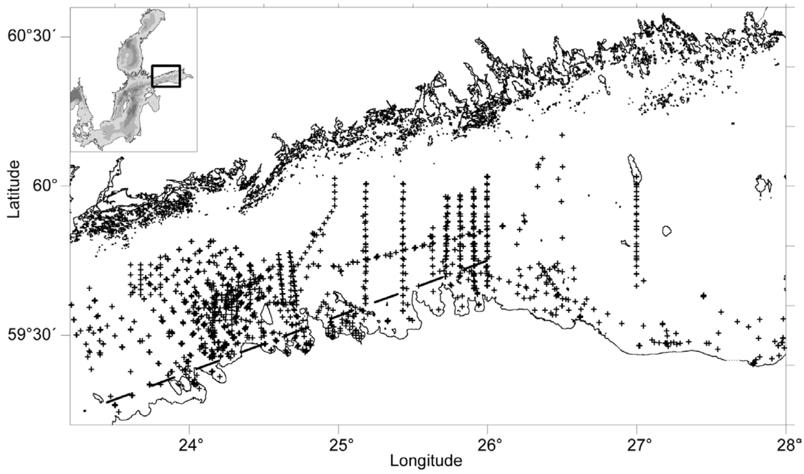

Fig. 1. Map of the Gulf of Finland. CTD cast locations are indicated with crosses and the reference line with a dashed line.

Altogether, the data from 2143 CTD casts, processed and stored as vertical profiles with a resolution of 0.5 m (1 m corresponds roughly to 1 dbar), were analyzed. A higher number of CTD casts was available from the south-western part of the Gulf of Finland (Fig. 1). The number of available profiles varied greatly from year to year (Table 1). We used only deep enough CTD casts in the analysis, whereas different depth limits were defined for different estimates. Profiles deeper or equal to 40 m were used in estimating the upper mixed layer (UML) depth, ≥ 60 m in estimating the base of thermocline and the cold intermediate layer parameters, ≥ 70 m in estimating the deep layer temperature and salinity and ≥ 80 m in estimating the gradients in halocline (and halocline presence).

We estimated the UML depth using smoothed (2.5 m moving average) vertical profiles of density. The UML depth was defined at each profile as the smallest depth where the density gradient exceeded a criterion defined on the basis of the density difference between the cold intermediate layer (CIL) and the UML (an example of the vertical temperature and density profiles and the corresponding estimates are shown in Fig. 2). This criterion (critical value) was calculated as follows:

$$\mathrm{Cr}_{\mathrm{up}} = (\rho_{\mathrm{cold}} - \rho_{\mathrm{min}})C_{\mathrm{up}}, \tag{1}$$

where ρ_{cold} is the density in the CIL at the depth of minimum temperature, ρ_{min} is the minimum density in the UML and $C_{\mathrm{up}} = 1/30\ \mathrm{m}^{-1}$. The latter is a constant, which was determined empirically in order to obtain the best performance of the criterion. In case of the characteristic density difference between the UML and CIL of 3 kg m^{-3}, $\mathrm{Cr}_{\mathrm{up}}$ equals 0.1 kg m^{-4}. Thus, the used criterion

Table 1. The number of available CTD casts by year and depth.

		Depth range (m)				
Year	Total	≤ 40	40–60	60–70	70–80	≥ 80
1987	402	68	122	82	88	42
1988	78	23	27	12	10	6
1989	388	78	74	87	111	38
1990	448	89	139	106	86	28
1991	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	32	20	5	1	3	3
1994	142	91	19	13	8	11
1995	33	19	6	4	1	3
1996	18	11	1	2	2	2
1997	138	16	78	31	11	2
1998	4	0	0	0	4	0
1999	9	4	5	0	0	0
2000	18	12	3	0	3	0
2001	57	47	4	1	1	4
2002	16	14	2	0	0	0
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	0	0	0	0
2006	187	32	84	28	36	7
2007	45	7	37	0	0	1
2008	128	17	23	8	59	21
Total	2143	548	629	375	423	168

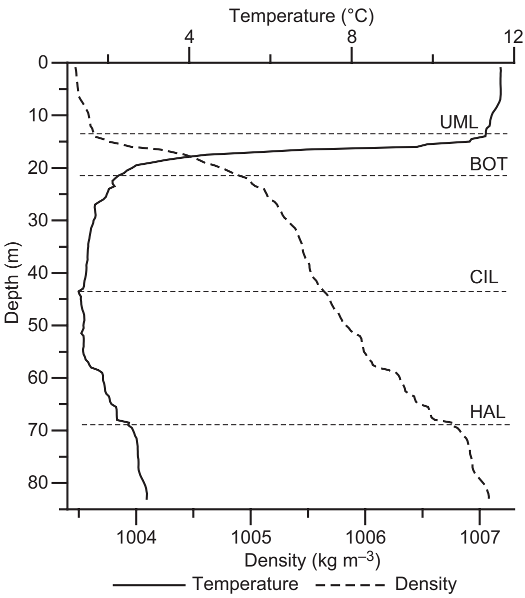

Fig. 2. An example of the vertical temperature and density profiles with the estimated characteristics of the termohaline structure: UML = upper mixed layer, BOT = base of the thermocline, CIL = cold intermediate layer, and HAL = center of the halocline.

was 3–10 times greater than that usually applied in estimating the open-ocean mixed-layer depth [*see* an overview by Thomson and Fine (2003)]. The base (lower border) of the thermocline was determined as the smallest depth where the temperature was below a critical value. The critical value was calculated as follows:

$$\mathrm{Cr}_{\mathrm{dp}} = T_{\min} + (T_{\max} - T_{\min})C_{\mathrm{dp}}, \quad (2)$$

where $T_{\min}$ is the minimum and $T_{\max}$ the maximum temperature at the current profile, and C_{dp} = 0.1. The latter constant was also determined empirically in order to obtain the best performance of the criterion.

The CIL temperature and depth were determined as the minimum temperature at the current profile and the depth corresponding to this minimum temperature record. Non-smoothed temperature profiles were used. The deep layer temperature, salinity and density were estimated at each profile as average temperature, salinity and density in the layer between 68 and 70 meters.

The center of the halocline was defined using smoothed salinity profiles (2.5-m moving average) as the maximum salinity gradient below the coldest point at the current profile. The halocline was determined only in case if the smoothed salinity gradient exceeded 0.07 m^{-1}.

The wind data were obtained from the Kalbådagrund meteorological station (Finnish Meteorological Institute) located in the central part of the Gulf. To characterize the large-scale meteorological forcing conditions in the region, we used the monthly-averaged BSI values calculated as the difference of normalized sea level pressure anomalies between Szczecin in Poland and Oslo in Norway (Lehmann *et al*. 2002; values provided by Andreas Lehmann).

Mean values of studied parameters were calculated stepwise as follows: first, monthly mean values of parameters as simple arithmetic means in a month in each year were found, secondly, monthly mean values for the whole study period were calculated taking into account only years with sufficient number of measurements and, finally, an overall mean was calculated on the basis of the obtained three monthly mean values. The sufficient number of measurements was defined as from > 7 CTD casts for the UML characteristics to > 3 CTD casts for the deep layer characteristics. Along-gulf and cross-gulf spatial variations were estimated using the above-mentioned procedures, respectively, for three longitudinal intervals (23.2–24.2°E, 24.2–25.2°E and 25.2–26.2°E, while for the UML salinity a longitudinal step of 0.5 was used) and for four distance intervals (0–10, 10–20, 20–30 and 30–40 km) where the distances were calculated from a reference line shown in Fig. 1.

Inter-annual variations of estimated parameters are presented and analyzed using the calculated, yearly (summer) mean values taking into account only these years where measurements from at least two summer months were available. The missing monthly-mean values were found by interpolation (extrapolation) using the existing monthly mean values from the same year and the average temporal evolution during the summer months (constructed for each parameter as described above). In order to relate the observed inter-annual changes to the atmospheric forcing, simple linear correlation coefficients between the characteristics of the vertical thermohaline structure and the BSI were calculated. Significance of diferences in salinity and temperature between years was tested with a *t*-test, under an assumption that data are normally distributed.

Results

Upper mixed layer

The overall mean UML derived from the available CTD casts in the Gulf of Finland in the summers of 1987–2008 was 12.8 m. On average, the UML depth was the smallest in June (11.4 m), slightly greater in July (12.1 m) and the greatest in August (14.9 m). Along the Gulf, the mean UML depth had relatively uniform distribution — the greatest UML depth (15.1 m) was found in the westernmost part of the Gulf between longitudes 23.2°E and 24.2°E, while in the two other regions the mean UML depth was close to 13.0 m (Fig. 3). Across the Gulf, the UML depth was on average greater near the southern coast than in the off-shore areas changing from 14.1 to 10.7 m. A remarkably higher variation of the UML depth was found in the coastal area — the standard deviation of the UML depth there was 7.4 m while in the off-shore areas (30–40 km from the reference line) it was 5.1 m.

The mean UML water temperature and salinity in summer in the Gulf of Finland were 15.2 °C and 5.2, respectively, while those in June were 11.8 °C and 4.9, respectively, in July 16.9 °C and 5.3, respectively, and in August 16.9 °C and 5.4, respectively. The mean UML temperature did not reveal any regular changes along the Gulf, but the mean UML salinity distribution increased from 4.3 in the eastern part of the study area (25.7–26.2°E) to 5.7 in the mouth of the Gulf of Finland (Fig. 3). Cross-gulf changes of the mean UML temperature and salinity were in the ranges of 15.7–16.4 °C and 5.1–5.3, respectively. The highest variations of the UML temperature and salinity were found near the coast where within the first distance interval of 0–10 km the corresponding standard deviations were 3.1 °C and 0.8, respectively.

Inter-annual variations in the UML temperature, salinity and depth were large, but no significant correlation was found with the BSI.

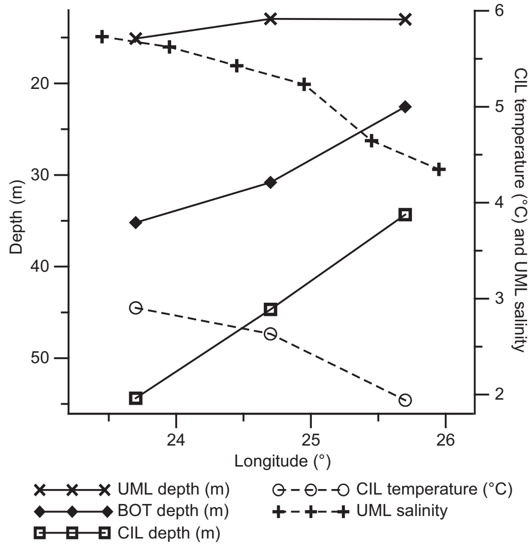

Fig. 3. Mean along-gulf changes of the UML, BOT, and CIL depths, as well as UML salinity and CIL temperature in the Gulf of Finland in the summers of 1987–2008. Estimates were made within the three longitudinal intervals (23.2–24.2°E, 24.2–25.2°E and 25.2–26.2°E) while for the UML salinity a longitudinal step of 0.5° was used.

Long-term changes of the mean UML temperature and salinity were estimated using the data from the two best covered periods: 1987–1990 and 2006–2008. The average July–August UML temperature and salinity were in 1987–1990 (mean ± SD) 16.42 ± 2.27 °C and 4.94 ± 0.68, respectively (the data from 862 CTD casts were used), and in 2006–2008 (mean ± SD) 16.91 ± 2.86 °C and 5.17 ± 0.70, respectively (253 CTD casts). Although an increase in both the UML temperature and salinity was found, due to the large short-term variability of these UML characteristics, the calculated mean values did not differ significantly.

Thermocline

The shallower border of the thermocline was defined to be equal to the UML depth, which was on average 12.8 m while the base of the thermocline was situated on average at 27.2 m; hence, the thermocline thickness was 14.4 m. The monthly mean depth of the base of the thermocline and corresponding thicknesses of the thermocline were in June 23.6 m and 12.2 m, respectively, in July 26.5 m and 14.4 m, respectively, and in August 31.6 m and 16.7 m, respectively. The base of the thermocline was at a greater depth in the mouth of the Gulf and smaller in the eastern part of the study area changing from 35.2 to 22.6 m (Fig. 3). Since the UML depth varied less in comparison with the rise of the base of the thermocline, the thermocline was remarkably thicker in the mouth area and thinner in the eastern part of the study area.

In order to quantify the variability of the thermocline characteristics, the probability distributions for some selected parameters were constructed. With a 75% probability, the UML depth was between 5 and 19 m, the base of the thermocline in a depth range of 17–37 m and the thickness of the thermocline between 6 and 22 m. For some thermocline parameters, clear maximum frequency ranges existed in probability distributions in a specific month (June, July or August) but in some other cases the distributions were more uniform and the variability was higher. For instance, the most frequent depth interval, where the base of the thermocline was detected, was in June 18–21 m (25% of cases) and in July 21–24 m (26% of cases) while in August no distinct maximum in the frequency distribution was observed. The thickness of the thermocline was in June in 83% of the cases between 4 and 16 m, but in July and August the variability of the thermocline thickness was much higher.

The mean vertical temperature gradient in the thermocline was –0.99 °C m^{-1} and the mean vertical salinity gradient 0.09 m^{-1}. In more than 70% of the cases, the absolute values of mean gradients in the thermocline were < 1.5 °C m^{-1} for temperature and < 0.2 m^{-1} for salinity. The mean vertical salinity gradient in the thermocline was stronger in June (0.12 m^{-1}) and weaker in July (0.08 m^{-1}) and August (0.07 m^{-1}). Although the smoothed density profiles revealed stable stratification, the negative vertical salinity gradients could be observed locally. At 5.5% of the profiles, inverse local salinity gradients exceeding 0.5 m^{-1} were detected. The steepest temperature gradient in the thermocline was most probably situated in a depth range of 12–21 m (52%). The steepest temperature gradients in each profile were mostly (75%) between 1 and 5 °C m^{-1}. The gradients > 8 °C m^{-1} were detected at < 5% of profiles.

Cold intermediate layer

The mean temperature of the coldest point of temperature profiles (CIL temperature) and its depth (CIL depth) in the Gulf of Finland in the summers of 1987–2008 were 2.5 °C and 42 m, respectively, whereas remarkable seasonal and inter-annual variations were detected. On average the CIL temperature rose during the summer as fast as 0.01 °C per day increasing from 2.0 in June to 2.8 in August. The CIL depth was increasing on average from 35 m in June to 47 m in August. The average CIL temperature was 2.9 °C in the mouth of Gulf and 1.9 °C in the eastern part of the study area (Fig. 3). The CIL depth revealed on average a similar trend: it was 54 m in the mouth area and 34 m in the eastern part of the study area (Fig. 3).

Large inter-annual variations in the CIL temperature were observed (Fig. 4) in the Gulf of Finland during the analyzed period 1987–2008. The lowest summer mean CIL temperature (1.3 °C) was measured in 1987 and the highest in 1990 and 2008 (3.4 and 3.6 °C, respectively). It could be expected that the summer CIL temperature depends strongly on the severity of previous winter. The correlation between the summer CIL temperature and the winter BSI was positive and the best correlation ($n = 8$, $r^2 = 0.81$, $p < 0.01$) was found if the mean BSI from January to February was used. The summer CIL temperature and the maximum ice extent in the Baltic Sea were (as expected) also correlated, but the correlation was negative ($n = 8$, $r^2 = 0.72$, $p < 0.01$).

Halocline and deep layer

The mean temperature and salinity at the 70 m depth in the Gulf of Finland in summer in 1987–2008 were 3.5 °C and 8.3, respectively. On average, a slight decrease in salinity from June to August of about 0.2 units and a slight increase in temperature of about 0.1 °C were detected. The average along-gulf changes in the deep layer temperature and salinity were also as

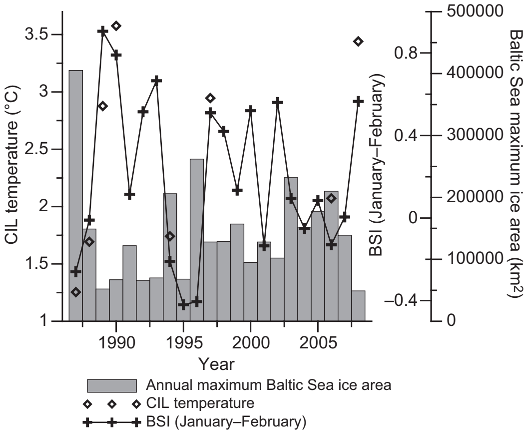

Fig. 4. Variability of the summer CIL temperature, BSI, and the annual maximum Baltic Sea ice area.

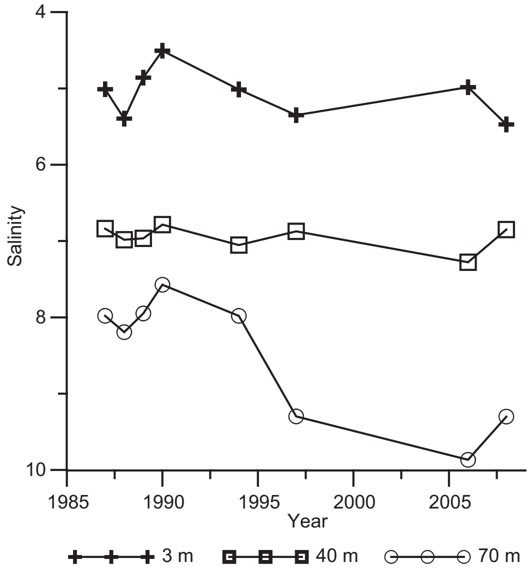

Fig. 5. Variation of the mean salinity at 3 m, 40 m and 70 m depths in the Gulf of Finland in the summers of 1987–2008.

low as 0.1 °C and 0.3, respectively, between the mouth area and the eastern part of the study area.

Inter-annual variability of the deep layer (70 m) temperature and salinity was quite high (Fig. 5). A group of years (1997, 2006 and 2008) with a higher summer mean salinity in a range of 9.1–9.8 and temperature in a range of 3.9–5.0 °C could be distinguished. On the other hand, in 1987–1990 and 1994 summer mean salinity was in a range of 7.7–8.2 and temperature in a range of 2.2–3.9 °C. Inter-annual variability of the salinity difference between the upper and deeper layers was in accordance with the mean deep layer (70 m) salinity changes (Fig. 5) although a slight increase in surface layer salinity between the years with a fresher and saltier deep layer could be noticed as well. The highest mean deep-layer salinity and the strongest mean vertical salinity gradients were recorded in 2006. However, it has to be noted that the intermediate-layer salinity (shown in Fig. 5 as the mean salinity at the 40-m depth) had much lower inter-annual variations than those in the surface layer and especially in the deep layer.

In order to elucidate the possible dependence of salinity gradients on the wind conditions, a correlation analysis between the deep layer and the surface-layer salinity difference at individual profiles, and the average wind speed and direction in the period preceding the measurement was performed. A significant correlation between the wind forcing and the salinity gradients was obtained if an average wind speed from a period of three weeks or longer (until a period of six weeks) before the CTD measurement was taken into account. The best (positive) correlation (n = 586, $r^2 = 0.33$, $p < 0.01$) was found with the average wind component from N-NE (20°).

The halocline was detected only if the smoothed vertical salinity gradient exceeded the value of 0.07 m^{-1}. The center of the halocline defined as the depth of the maximum salinity gradient was in the Gulf of Finland in the summers of 1987–2008 on average at the depth of 67 m. In the years described above as those with fresher deep layer waters, the center of the halocline was found on average at the 71-m depth, and in the years 1997–2008 on average at the 64-m depth. It has to be mentioned that also at 22% of analyzed profiles in the years before 1997, the maximum vertical salinity gradient was < 0.07 m^{-1}, and the halocline was not detected at all, while in the years 1997, 2006 and 2008, the halocline was present at all profiles.

Vertical structure

In order to compare the vertical temperature and salinity distribution in the two distinct periods (fresher and saltier deep layer in the Gulf

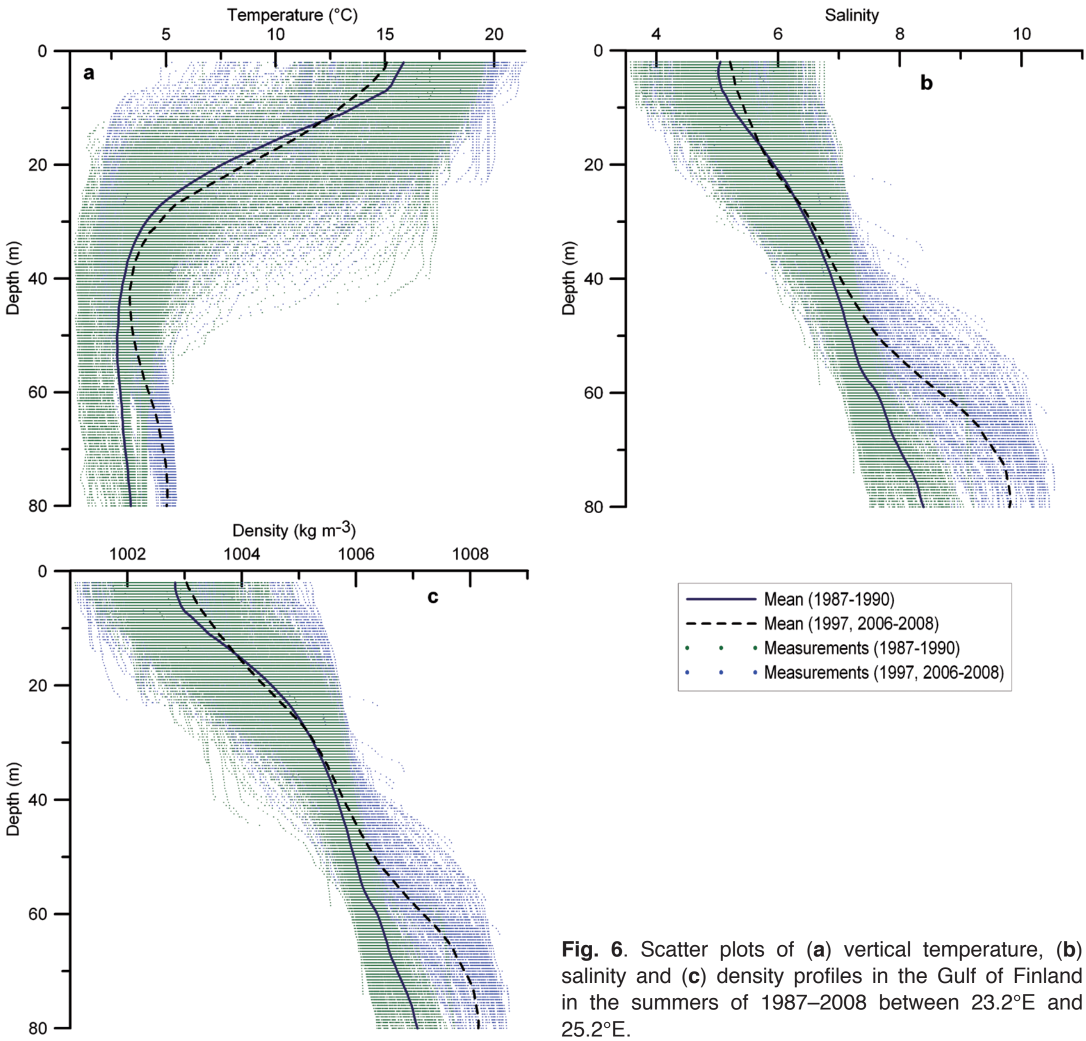

Fig. 6. Scatter plots of (**a**) vertical temperature, (**b**) salinity and (**c**) density profiles in the Gulf of Finland in the summers of 1987–2008 between 23.2°E and 25.2°E.

of Finland) we extracted sub-sets of data from both groups (years 1987–1990 and years 1997, 2006–2008), and restricted the geographical area to the longitudes between 23.2°E and 25.2°E. It was done to be sure that all summer months are well covered and the data are collected from the same area within both periods. The overall scatter plot of the vertical temperature and salinity profiles available from those summers in the western Gulf of Finland (Fig. 6) revealed a quite large variability of temperature and salinity throughout the entire water column, especially in the surface and thermocline layer for temperature and in the surface and deep layer for salinity. Although the variability was high in the surface layer, the profiles did not form two separate groups in the upper layers down to the CIL depth. At the same time, the years 1997 and 2006–2008 grouped clearly as those with saltier and warmer waters in the deep layer of the Gulf of Finland.

The mean vertical profiles showed a clear difference in the temperature and salinity distribution in the deep layer as well (Fig. 6). The estimated mean values of temperature and salinity at the 70 m depth in the years 1987–1990 were 3.1 °C and 8.0, respectively, and in the years 1997, 2006–2008, 4.9 °C and 9.5, respectively. The mean deep-layer temperature and salinity for these two groups are statistically different (*t*-test: df = 544, $p < 0.05$). In addition, in the years with saltier waters, the CIL temperature was higher and the CIL depth lower. The mean values of the

CIL depth, CIL temperature and salinity at the CIL depth in the western Gulf (from 23.2°E to 25.2°E) in the years with less-saline and more-saline waters were 46 m and 39 m, 2.5 °C and 2.9 °C, and 7.0 and 7.0, respectively.

Since UML salinity and temperature observed in the years with a saltier deep layer did not differ statistically, the vertical density gradient through the seasonal thermocline during those years was close to or even smaller than that in the years with a fresher deep layer. At the same time, a significantly stronger vertical stratification was present in the deep layer in 1997, 2006–2008 (Fig. 6c). The estimates of the mean density difference between the deep layer (70 m) and the intermediate layer (40 m) in these two groups of years were 1.1 kg m^{-3} (1987–1990) and 2.1 kg m^{-3} (1997, 2006–2008), and between the intermediate layer (40 m) and the surface layer (3 m) 2.8 kg m^{-3} (1987–1990) and 2.7 kg m^{-3} (1997, 2006–2008). In conclusion, the vertical structure of the water column in the Gulf of Finland could be approximated in 1987–1990 mainly as a two-layer structure, and in the years 1997, 2006–2008 clearly as a three-layer structure.

We also divided the years into two groups on the basis of the CIL temperature. The years 1989, 1990, 1997 and 2008 were classified as those with a higher CIL (2.8–3.6 °C), and the years 1987, 1988, 1994 and 2006 as those with a lower CIL (1.3–2.1 °C). Vertical profiles of temperature did not form clear groups in the scatter plot but the mean CIL temperature differed statistically between the warmer (3.2 °C) and colder years (1.5 °C), and in the colder years the mean temperature was lower throughout the entire water column.

Discussion and conclusions

Inter-annual variations in the UML temperature and salinity in the Gulf of Finland were estimated using the available CTD casts from 1987–2008. Although a positive UML temperature trend could be detected supporting the earlier results (Siegel *et al*. 2006, Suikkanen *et al*. 2007), the variability in the UML temperature within the groups of years (1987–1990 and 2006–2008) was too large to unequivocally confirm the increase in the sea surface temperature. Thus, the CTD casts collected during different programs and projects could not serve as a basis for long-term trend estimates (if used alone) due to high variability in the UML characteristics.

The inter-annual variations in CIL temperature agreed quite well with severity of a preceding winter and the BSI in January–February. According to the classification of the maximum annual extent of ice cover in the Baltic Sea (Seinä and Palosuo 1996), the winter 1986/1987 was extremely severe and the winters 1988/1989 and 1989/1990 were extremely mild. These extremes resulted in the lowest CIL temperature in summer 1987 and much higher CIL temperatures in 1989 and 1990. The highest CIL temperature was observed in 1990 probably due to the two preceding consecutive mild winters. A similar relationship between the winter atmospheric forcing and the CIL temperature in the Baltic Sea basins (except the Gulf of Finland and the Gulf of Bothnia) was described by Hinrichsen *et al*. (2007).

The changes in deep-layer temperature and salinity depend on two processes. The detected clear difference between the years 1987–1990 and 1997, 2006–2008 was most probably caused by a major inflow of the North Sea waters into the Baltic Sea in 1993 that interrupted the stagnation in the Baltic Proper deep layers (Matthäus and Lass 1995) and further inflows, as that observed in 2003 (Feistel *et al*. 2003). On the other hand, Elken *et al*. (2003) described a relationship between the deep-layer salinity changes and the wind-driven circulation in the Gulf of Finland. They showed that the wind-induced surface transport out of the Gulf is most intensive in case of the winds from NE while the reaction time is about 15 hours. In 2006, when the northerly and easterly winds dominated for a long period, a large inflow of saltier waters into the Gulf of Finland deep layer took place (Lips *et al*. 2008). In accordance with those findings, we showed that a linear correlation exists between the average wind component from N-NE and the salinity difference between the deep layer and the surface layer. This relationship was significant when the averaging period longer than three weeks was used indicating that the wind forcing effect is seen in the vertical salinity distribution after a relatively long period of winds supporting or working against the ordinary estuarine circulation with an inflow in the surface layer and an outflow in the deeper layers.

The most evident difference in the vertical temperature and salinity distributions between the years 1987–1990 and 1997, 2006–2008 was observed in the deep layer: in the earlier period, the halocline was weak or absent, while in the latter one the halocline was much stronger. By analyzing historical monitoring data and numerical modeling results, simultaneous temporal changes of salinity have been shown to take place throughout the entire water column in the Gulf of Finland (Omstedt and Axell 2003), and such simultaneous changes of salinity are predicted also in the Baltic Sea in case of the scenario with a salinity decrease (e.g. Meier 2006). We showed that while large changes were observed in the deep layer, the intermediate-layer mean salinity remained almost unchanged. This feature can be explained by the different mixing depths in winter in the years with a strong halocline and in the years with a weak halocline. Weak stratification allows for winter mixing to penetrate into deeper layers causing an upward salt flux and in turn almost the same salinity in the cold intermediate-layer of the Gulf of Finland than that in the years with more saline deep water and strong stratification (and consequently a shallower mixing depth in winter). It leads to an important consequence for the planktonic ecosystem: the vertical stratification in the seasonal thermocline will not change very much even if the salinity of deep layers changes remarkably.

The climate change scenarios predict that the Baltic Sea will be most probably warmer and fresher at the end of this century (Meier 2006, BACC 2008). The large variability of the temperature and salinity fields observed within the last 22 years enables us to foresee the possible changes in the vertical thermohaline structure. We suggest that if the above scenario realizes, the Gulf of Finland water column will be mixed down to the greater depths during winter and it will have most likely the two-layer structure in summer. However, if the water temperature rises both in winter and summer (*see* BACC 2008), the vertical gradients in the seasonal thermocline will rather increase than decrease, due to the fact that an increase of the CIL temperature (which is close to the temperature of maximum density) will influence the density less than that in the UML.

In conclusion, we showed that the vertical structure of temperature and salinity fields has experienced large variations. The years under consideration (1987–2008) can be divided into two distinct groups of years with the statistically different mean temperature and salinity in the deep layer (1987–1990: fresher and colder deep layer; 1997, 2006–2008: saltier and warmer deep layer). While the overall salinity (and density) gradient in 1997, 2006–2008 was much stronger as well as the halocline was sharper, the intermediate layer salinity and consequently the vertical salinity (density) gradient in the seasonal thermocline did not reveal large changes between these two periods. We suggest that a possible change towards fresher waters in the Baltic Sea will lead to a weakening of the halocline in the Gulf of Finland deeper areas and the water column (and flow pattern) will have a two-layer structure in summer. At the depths of the seasonal thermocline, the vertical gradient of salinity will not decrease simultaneously and a possible increase of sea surface temperature could lead to a strengthening of the vertical density stratification in the thermocline.

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